Single-Nanofiller Modification of Epoxy Adhesives for Bonded GFRP Composite Joints: A Strengthened Static Screening Study

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Abstract: The use of epoxy adhesives has grown rapidly in polymer-composite assemblies because they can transfer load across a continuous bonded area and do not require drilling or fibre interruption. The static reliability of epoxy-bonded glass-fibre-reinforced polymer (GFRP) joints, however, could be limited by the brittleness of the cured network, and the issues of bond-line defects and the selection of an appropriate single-nanofiller modifier. This work is a statistically validated screening of single nanofiller epoxy adhesives of bonded GFRP composite joints. From the broader experimental results, six different adhesive systems were chosen: neat epoxy (F14), 0.3 wt% multi-walled carbon nanotube (MWCNT)/epoxy (F6), 1 wt% graphene nanoplatelet (GNP)/epoxy (F7), 0.5 wt% silica/epoxy (F9), 0.5 wt% clay/epoxy (F11) and 0.3 wt% boron nitride (BN)/epoxy (F13). The following performance measures were used in this evaluation of the selected systems: peak tensile load in single lap-joint loading, flexural strength in three-point bending, dispersion measures, 95% confidence intervals, Welch ANOVA, Games-Howell comparisons, normalized cross-loading performance, and macroscopic failure evidence. The MWCNT/epoxy formulation exhibited the highest mean peak tensile load being 123.1% higher than neat epoxy. The highest mean flexural strength (67.50 MPa) was recorded for MWCNT/epoxy and GNP/epoxy, which were 328.6% higher than neat epoxy. Moderate improvements were observed with silica and clay while BN at the loading tested was limited in mechanical improvement. Structural qualification considerations of repeatability, dispersion control and evidence of failure make these findings practically significant because carbon single-nanofiller systems, specifically MWCNT and GNP are identified as the most promising baseline modifiers to improve the static capacity of epoxy-bonded GFRP joints.

Keywords: Nanocomposite adhesive, GFRP joint, carbon nanotube, graphene nanoplatelet, silica nanoparticle, flexural response, static screening.

1. INTRODUCTION

Adhesive bonding is a viable joining technique for composite structures because it can transmit load across the bonded area without introducing holes, fibre interruption or local stress concentrations associated with mechanical fastening. In composite assemblies, the joint response is governed not only by the bulk adhesive but also by adherend stiffness, overlap geometry, bond-line thickness, surface preparation, curing history, loading eccentricity and the local peel/shear stress state near the overlap ends [1-3]. Consequently, the performance of a polymer adhesive in a bonded single-lap configuration cannot be interpreted as an intrinsic bulk adhesive property alone; it must be evaluated at the joint level.

Epoxy adhesives are frequently used for composite bonding because of their high cohesive strength, low curing shrinkage, dimensional stability and compatibility with many engineering substrates. Their main limitation is the relatively brittle fracture behaviour of the cured thermoset network, particularly under mixed-mode loading, local defects and weak interfacial regions that initiate cracks. One established strategy for modifying this response is the incorporation of nanoscale fillers into the epoxy matrix. Improvements in stiffness [4], crack-path tortuosity [5-7], energy dissipation [5,6], load transfer and interphase behaviour [5,6,8] depend strongly on filler morphology, filler loading, dispersion quality and the resulting processability of the adhesive.

Previous studies have investigated individual nanofiller-reinforced epoxies, selected hybrid systems or specific bonded-joint geometries; however, direct comparison across several nanofiller families is often complicated by differences in adherend material, surface treatment, filler concentration, curing route, test configuration and reported mechanical indicators. A compact single-filler baseline is therefore needed before more complex hybrid systems can be interpreted rationally. In particular, improvement over neat epoxy alone does not prove that a filler family is robust for bonded GFRP joints; the response should also be judged against repeatability, cross-loading behaviour and failure evidence obtained under the same experimental route.

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The novelty of this work is that five different nanofiller families--MWCNT, GNP, SiO2, clay and BN--are screened within the same epoxy-bonded GFRP joint system using identical preparation, geometry and static testing conditions. Unlike studies that focus on a single nanofiller or report only one loading mode, this paper combines peak tensile load, flexural strength, variability, normalized cross-loading response, Welch-type statistical testing and macroscopic failure evidence. This integrated screening provides a clearer basis for selecting single-nanofiller modifiers for structural adhesive applications and for identifying when a high mean value must be interpreted cautiously because of scatter or possible processing sensitivity.

2. CRITICAL BACKGROUND AND LITERATURE POSITIONING

Recent reviews indicate that adhesively bonded composite joints should be treated as multi-mechanical systems rather than simple material coupons. Joint capacity, stiffness, deformation, crack development and failure location may respond differently to the same adhesive modification and may also vary with loading mode [2,10-12]. This is particularly important for nanofilled epoxy adhesives because a filler can increase one response while simultaneously increasing viscosity, agglomeration sensitivity or scatter in another response.

Carbon nanotubes are attractive modifiers because their high aspect ratio can support stress transfer, microcrack-bridging-like behaviour and pull-out-type energy dissipation when dispersion and interfacial compatibility are adequate [4-6,15,17,21]. GNPs provide a different carbon morphology: their planar geometry can promote local load redistribution, crack deflection and interfacial energy dissipation [9,22-24]. However, both filler families are sensitive to mixing quality and concentration. Insufficient dispersion, local clustering or excessive filler loading may create agglomerates that behave as stress concentrators and reduce the repeatability of the joint response [5,8,9,23].

Other non-carbon nanofillers, like silica nanoparticles, clay platelets and BN particles, offer alternative modification avenues. The toughness or the crack-pinning resistance can be increased based on the distribution of the particles and the quality of the bond-line and the bond-line-matrix adhesion, depending on nanosilica [7,13]. The optimum amount of layered clay for influencing adhesion, stiffness and fatigue related behaviour is dependent on the mixing route and the type of joint [16,17]. BN can be used to impart stiffness, thermal and multifunctional properties in polymer formulations, but its mechanical properties in bonded joints need to be demonstrated for the specific adhesive, adherend and geometry used [5,6,16,17].

Table **1** shows that the present study is compared to the representative literature. The main gap filled in here is that a great number of families of single nanofillers have not been subjected to a concise, same system screening in both tensile and bending indicators in the context of epoxy bonded GFRP joints. Thus, this present manuscript takes a focused approach on single-filler systems, and does not include the effect of dual-filler combinations, thereby allowing the contribution of each individual filler family to be understood without the interfering effects of dual-filler combinations.

3. MATERIALS AND METHODS

Six adhesive systems were selected from the permanent experimental coding scheme used in the wider doctoral work. Neat epoxy (F14) was retained as the reference control, while five single-nanofiller epoxy adhesives--F6, F7, F9, F11 and F13--were selected to represent tubular carbon, planar carbon, rigid inorganic particle, layered silicate and ceramic nitride filler families, respectively. Hybrid formulations were intentionally excluded from this manuscript because the objective was to establish single-filler baseline behaviour before cooperative or antagonistic dual-filler effects are discussed elsewhere. The selected formulations and their experimental roles are summarized in Table **2**.

The selected nanofiller contents were chosen as literature-supported, experimentally workable loading levels rather than as a full factorial optimization of all possible concentrations. The 0.3 wt.% MWCNT level was selected to exploit high-aspect-ratio carbon reinforcement while limiting the viscosity increase and agglomeration risk commonly associated with nanotube addition [4-6,15,17,21]. The 1 wt.% GNP level was chosen to represent a practical platelet-carbon loading capable of promoting load redistribution and crack-path modification while remaining within a processable range for epoxy adhesives [9,22-24]. The 0.5 wt.% SiO2 and 0.5 wt.% clay levels were selected as moderate inorganic and layered-silicate contents that could provide measurable stiffness or crack-pinning effects without intentionally overloading the bond line

Table 1: Literature-Positioning Matrix Used to Frame the Present Single-Nanofiller Screening Study

Reference group	Literature focus	Main evidence from literature	Role in the present paper
Banea and da Silva [1]; Kupski and Teixeira de Freitas [3]	Composite adhesive bonding and lap-joint mechanics	Bonded joints are governed by adherend geometry, load eccentricity, peel/shear coupling and interface quality.	The present paper reports joint-level peak load and bending response rather than claiming intrinsic adhesive tensile strength.
Jojibabu *et al*. [4]; Guchait *et al*. [5]; Gonçalves *et al*. [6]	Epoxy nanocomposite adhesives	Nanofiller morphology, dispersion and matrix compatibility control whether reinforcement improves or degrades performance.	The selected single fillers are interpreted through morphology-specific mechanisms and processing risk.
Sprenger [7]; Zhou *et al*. [13]	Nanosilica/epoxy systems	Rigid silica particles may improve toughness and crack pinning but can be sensitive to loading and dispersion.	F9 is used as the inorganic-particle reference against carbon and clay systems.
Chu *et al*. [16]; Cakir and Kinay [17]	Clay and multiple single-filler comparisons	Layered clay can affect adhesion, fatigue and strength, but optimum levels depend on mixing and joint configuration.	F11 provides the layered-silicate single-filler reference.
Dong *et al*. [9]; Akter *et al*. [23]; Venugopal and Sudhagar [22]; Abdalla *et al*. [24]	Graphene/GNP epoxy and joint studies	Platelet geometry can promote crack deflection and load redistribution, but dispersion remains critical.	F7 tests whether GNP alone can provide balanced static performance.
Eryildiz *et al*. [15]; Rao *et al*. [21]	MWCNT/GNP adhesive-joint literature	Carbon nanotubes and graphene can improve joint capacity through high-aspect-ratio and platelet reinforcement.	F6 and F7 are the carbon single-filler baselines retained for Q4 publication.

Table 2: Selected Formulations Included in the Q4 Single-Nanofiller Manuscript

Code	Adhesive system	Nanofiller content	Experimental role
F14	Neat epoxy	0	Baseline control for all percentage-change calculations
F6	MWCNT/epoxy	0.3 wt.% MWCNT	Tubular carbon nanofiller; high-aspect-ratio reference
F7	GNP/epoxy	1 wt.% GNP	Planar carbon platelet reference
F9	SiO2/epoxy	0.5 wt.% SiO2	Rigid spherical inorganic nanoparticle reference
F11	Clay/epoxy	0.5 wt.% clay	Layered silicate reference
F13	BN/epoxy	0.3 wt.% BN	Ceramic nitride platelet/reference filler

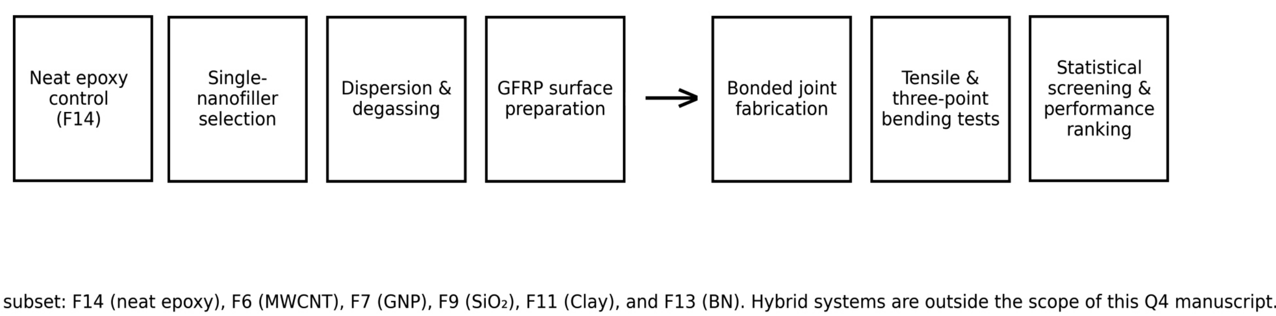

Figure 1: Experimental screening workflow used for the selected single-nanofiller epoxy/GFRP joint systems.

[7,13,16,17]. The 0.3 wt.% BN level was used as a low ceramic-nitride reference to test whether BN could provide mechanical benefit in this specific epoxy/GFRP joint system. Overall, the concentration selection was guided by the need to balance reinforcement potential, dispersion quality, adhesive processability and wetting of the GFRP adherends [4-8,17].

Prior to bonding, the adherends cut from GFRP laminate were surface-treated using the same preparation route before bonding. The mixing order of epoxy resin-hardener system was the same for all groups selected. The mass of fillers needed for the nanofilled systems was added to the adhesive prior to the bonding process; the neat epoxy was used as a reference material. All selected formulations were tested and analyzed with the same specimen geometry and preparation method, thus allowing for direct comparison.

The single lap joint test specimens were bonded for tensile loading based on the same reasoning as that used for the fibre-reinforced-plastic bonded-joint test [25]. This screening paper reports the principal tensile indicator, which is directly measured by the machine, Fm (kN). This conservative reporting does not report the tensile response as an intrinsic adhesive tensile strength and the interpretation is limited to the tested bonded-joint structure. Representative load-displacement curves were also checked to ensure that the peak loads were real loads on the specimens and not isolated numerical entries in the exported machine records.

The flexural response of the bonded GFRP specimens was assessed by three-point bending tests based on the principles of flexural testing with reinforced plastic (RP) [27]. The main bending indicator was flexural strength Rbb (MPa). The terminology for failure interpretation was based on that used for fibre-reinforced-plastic bonded joints [26]. The proposed mechanisms are evidence-consistent, mechanical response- and literature-based, and presented as a possible explanation, not as a direct observation of the microstructural features of the fracture surface by SEM and other microscopic observation techniques for this manuscript.

Retained samples were analysed for each formulation of the mean, sample standard deviation, coefficient of variation, minimum, maximum, 95% confidence interval and percentage change from neat epoxy. Welch ANOVA was applied instead of classical equal-variance ANOVA, due to the small experimental groups and variances were not assumed to be equal [28,30]. The Games-Howell post-hoc comparisons were then used, as they are appropriate for unequal variances and group sizes [29]. Normalized tensile and bending values were also determined to provide a screening cross-loading value.

4. RESULTS

The maximum tensile-load response is summarized in Table **3** and in Figure **2**. The mean peak tensile load of the neat epoxy control (F14) was obtained as 1.8535 kN. The MWCNT/epoxy formulation (F6) achieved the highest mean value (4.1345 kN), which is 123.1% higher than neat epoxy. GNP/epoxy (F7) was the second highest with 3.7580 kN, an increase of 102.8%. Silica/epoxy (F9) exhibited moderate enhancement of 13.9% while the clay/epoxy (F11) and BN/epoxy (F13) composites exhibited reduction of 8.7% and 35.3% respectively when compared with neat epoxy.

The tensile results indicate that the advantage of F6 was not only its high mean peak load but also its repeatability. The coefficient of variation for F6 was very low (0.90%), whereas F7 showed a higher tensile CV (17.13%). This distinction is important for structural adhesive screening because a high mean response must be interpreted together with scatter. A formulation that produces high capacity but wide dispersion may require tighter control of dispersion, wetting or bond-line formation before being treated as a robust engineering candidate. As shown in Figure **3**, the representative tensile load-displacement curves of the carbon-modified systems reached higher load levels than the neat epoxy and non-carbon single-filler systems.

Welch ANOVA confirmed a statistically significant formulation effect on peak tensile load, $F(5, 7.45) = 517.06$, $p < 0.001$ (Table **5**). The Games-Howell comparisons provided in the accompanying statistical workbook showed that F6 was clearly separated from the lower-capacity neat epoxy, silica, clay and BN groups. This supports the interpretation that 0.3 wt.% MWCNT was the strongest single-filler modification for tensile-load capacity within the selected subset.

Table 3: Peak Tensile-Load Statistics for the Selected Adhesive Systems

Code	Formulation	n	Mean Fm (kN)	SD	CV (%)	95% CI (kN)	Change vs neat (%)	Rank
F14	Neat epoxy	4	1.853	0.177	9.56	1.571-2.136	0.0	5
F6	0.3 wt.% MWCNT	4	4.135	0.037	0.90	4.075-4.194	123.1	1
F7	1 wt.% GNP	4	3.758	0.644	17.13	2.734-4.782	102.8	2
F9	0.5 wt.% SiO_2	4	2.112	0.464	21.96	1.374-2.850	13.9	3
F11	0.5 wt.% Clay	4	2.015	0.216	10.74	1.671-2.359	8.7	4
F13	0.3 wt.% BN	4	1.200	0.106	8.80	1.032-1.367	-35.3	6

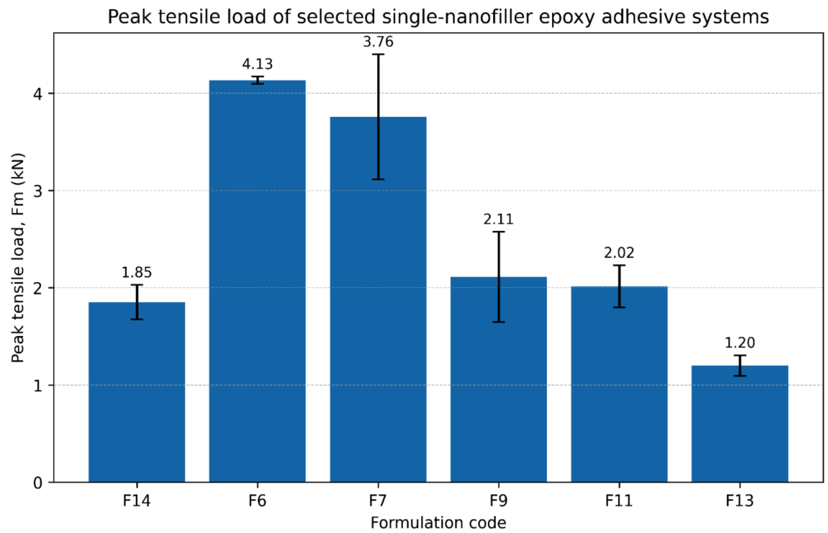

Figure 2: Peak tensile-load comparison for neat epoxy and single-nanofiller epoxy adhesives.

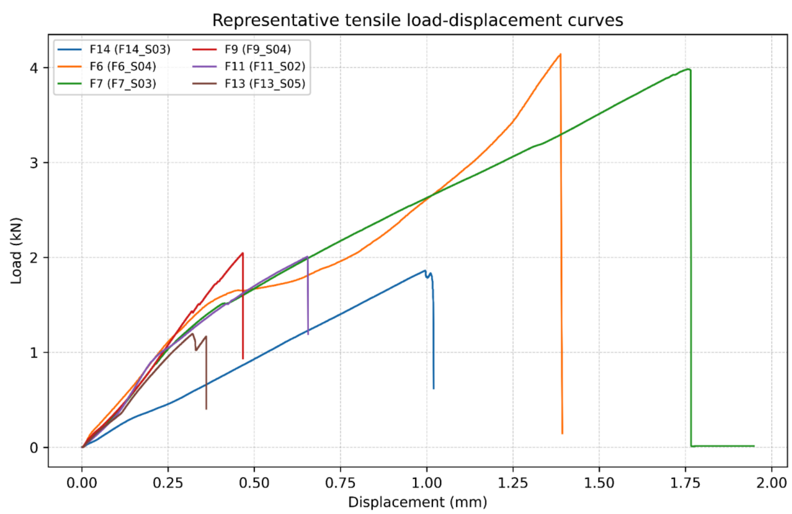

Figure 3: Representative tensile load-displacement curves for the selected adhesive systems.

The flexural-strength results are summarized in Table **4** and Figure **4**. The neat epoxy control achieved a mean flexural strength of 15.75 MPa. MWCNT/epoxy (F6) and GNP/epoxy (F7) both reached 67.50 MPa, corresponding to a 328.6% increase relative to neat epoxy. Silica/epoxy (F9) reached 37.50 MPa (+138.1%), clay/epoxy (F11) reached 27.75 MPa (+76.2%) and BN/epoxy (F13) reached 18.50 MPa (+17.5%). These values show that the carbon fillers provided the highest bending capacity, but they also demonstrate that tensile and flexural ranking should be interpreted separately because F6 and F7 were equivalent in mean bending response but not in mean tensile-load response.

Bending variability must be considered together with mean flexural strength. F6 produced the joint-highest mean Rbb but also showed a high flexural CV, while F7 showed substantial but lower flexural scatter. In nanofilled epoxy systems, this type of dispersion can arise from local differences in filler distribution, agglomeration, wetting continuity, bond-line uniformity or damage initiation under the bending stress field [5,8,9,23]. BN showed low flexural scatter, but its mean mechanical gain was limited. Therefore, the results confirm that mean strength alone is not sufficient for formulation selection; repeatability and failure evidence are also required.

The formulation effect on flexural strength was also statistically significant according to Welch ANOVA, $F(5, 7.66) = 14.42$, $p < 0.001$ (Table **5**). The scatter plot in Figure **6** and the normalized performance matrix in

Table 4: Flexural-Strength Statistics for the Selected Adhesive Systems

Code	Formulation	n	Mean Rbb (MPa)	SD	CV (%)	95% CI (MPa)	Change vs neat (%)	Rank
F14	Neat epoxy	4	15.75	1.89	12.02	12.74-18.76	0.0	6
F6	0.3 wt.% MWCNT	4	67.50	49.99	74.06	-12.05-147.05	328.6	1
F7	1 wt.% GNP	4	67.50	25.12	37.21	27.53-107.47	328.6	1
F9	0.5 wt.% SiO_2	4	37.50	5.45	14.52	28.83-46.17	138.1	3
F11	0.5 wt.% Clay	4	27.75	3.95	14.23	21.47-34.03	76.2	4
F13	0.3 wt.% BN	4	18.50	1.00	5.41	16.91-20.09	17.5	5

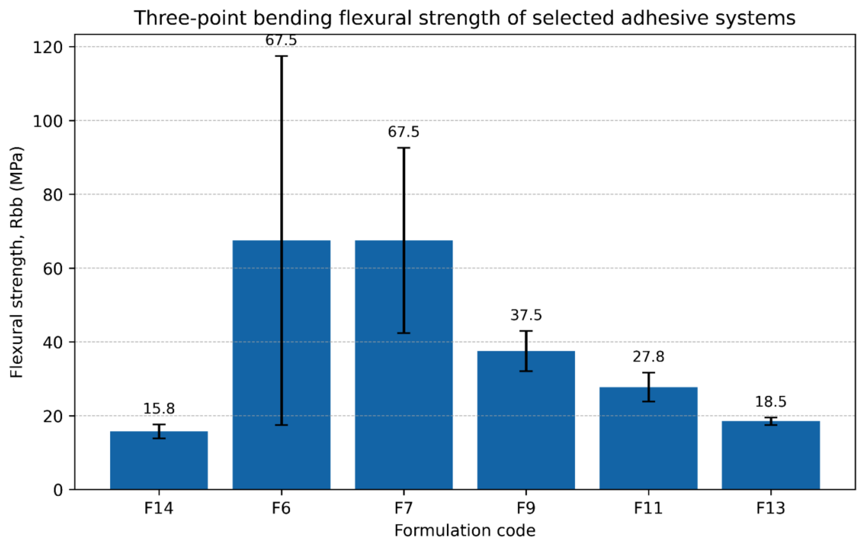

Figure 4: Flexural-strength comparison for neat epoxy and single-nanofiller epoxy adhesives.

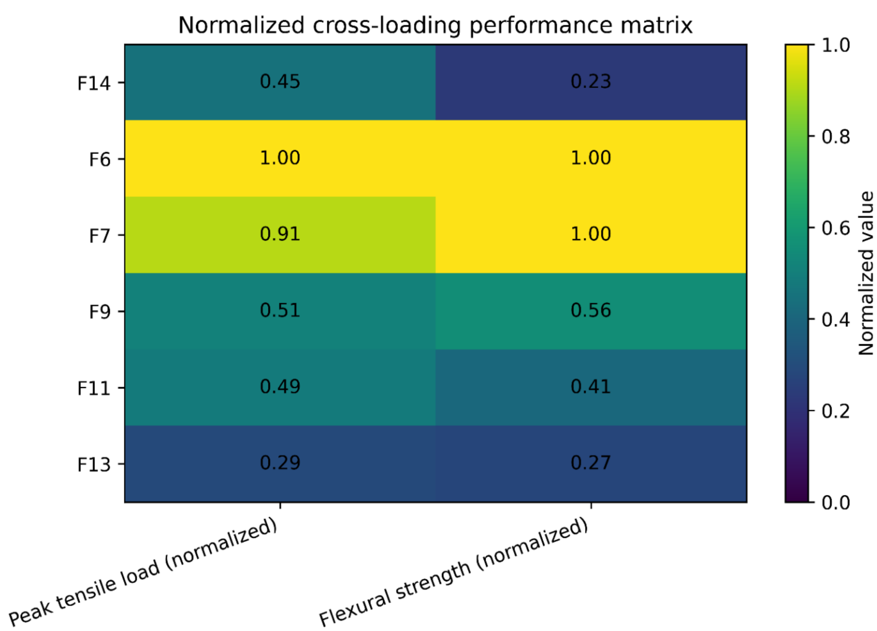

Figure 5: Normalized tensile-flexural performance matrix for the selected single-filler systems.

Table 5: Welch ANOVA Summary for the Selected Single-Filler Manuscript

Response	F	df1	df2	p-value	Interpretation
Tensile peak load Fm	517.06	5	7.45	<0.001	Significant formulation effect
Flexural strength Rbb	14.42	5	7.66	<0.001	Significant formulation effect

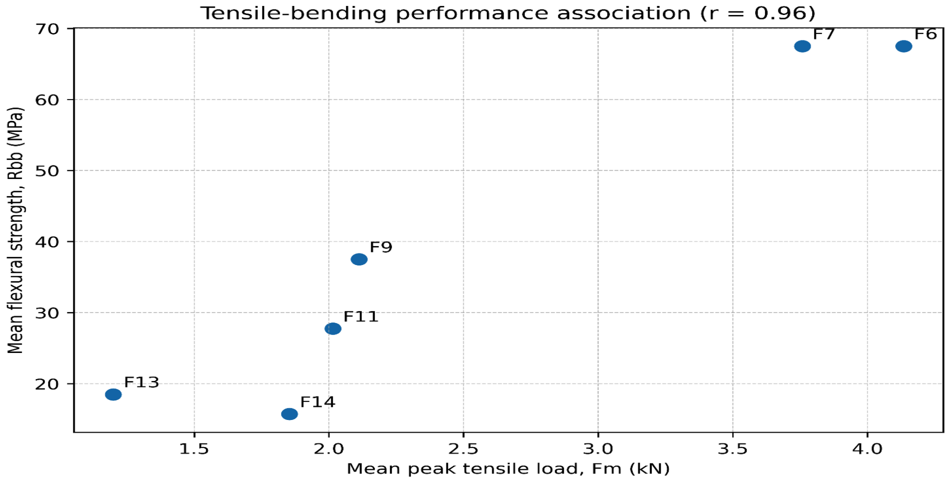

Figure 6: Relationship between mean peak tensile load and mean flexural strength across the selected systems.

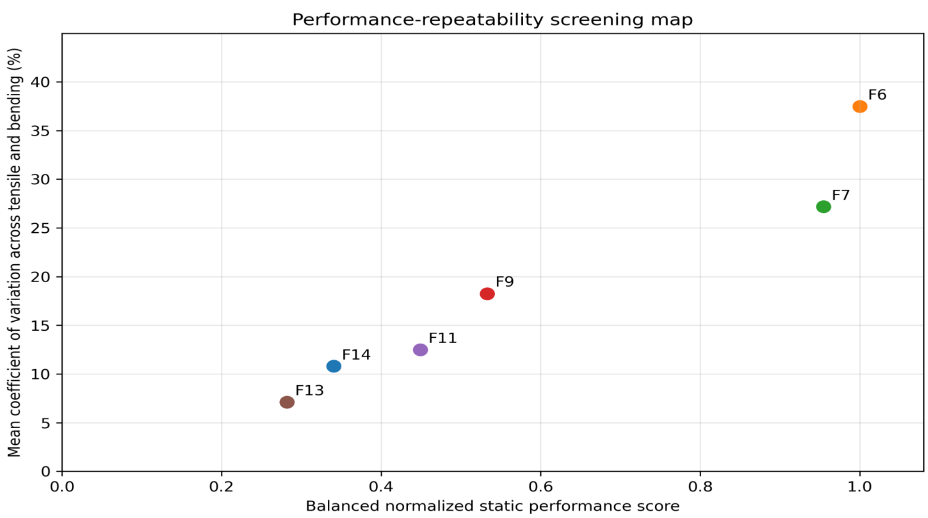

Figure 7: Performance-repeatability screening map showing balanced normalized performance versus mean coefficient of variation.

Figures **5** and **6** show that F6 and F7 occupied the high-performance region of the design space, F9 and F11 occupied an intermediate region, and F13 remained close to or below the neat epoxy reference depending on the response considered. The performance-repeatability map in Figure **7** therefore helps distinguish high-capacity carbon systems from moderate or limited-benefit fillers while showing that variability remains an important practical constraint.

Representative macroscopic failure evidence is shown in Figure **8**. The photographs show retained adhesive, mixed adhesive/cohesive regions, exposed woven-fibre surfaces and localized substrate-involved damage. These observations are consistent with composite bonded-joint failure under non-uniform local stress fields and variable bond-line quality. However, because the fracture surfaces were not examined by SEM or optical microscopy, the images should be interpreted as macroscopic evidence only. They support the mechanical interpretation but do not independently prove nanofiller dispersion, crack bridging or crack deflection at the microscale.

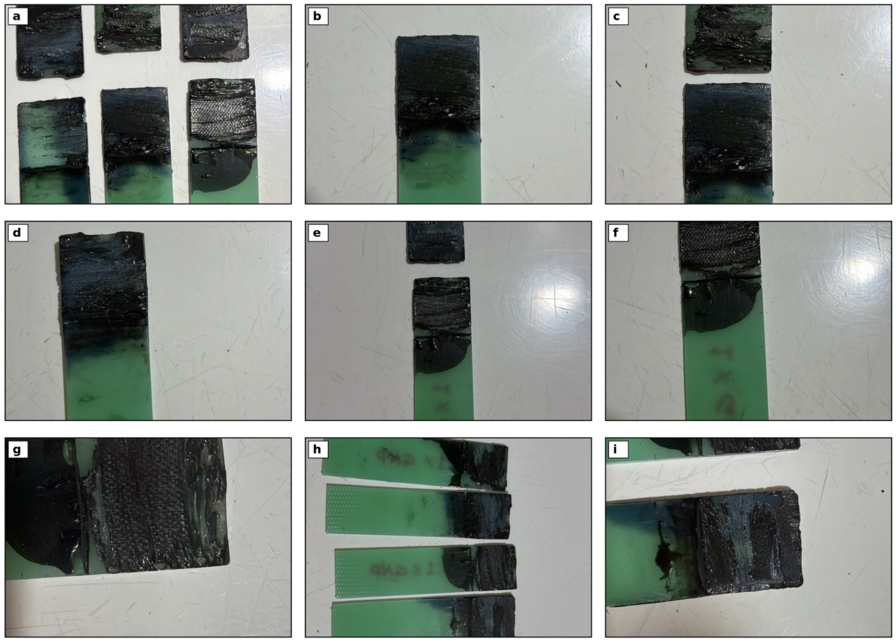

Figure 8: Representative macroscopic failure evidence for epoxy-bonded GFRP specimens, showing retained adhesive, mixed failure regions, exposed woven-fibre texture and local substrate-involved damage.

5. DISCUSSION

The central result of this study is that the carbon-based single nanofillers were the most effective modifiers for the investigated epoxy/GFRP bonded-joint system. MWCNT/epoxy produced the highest mean tensile capacity and tied with GNP/epoxy for the highest mean flexural strength. This behaviour is consistent with the high-aspect-ratio morphology of nanotubes, which can support stress transfer and crack-bridging-like resistance when they are sufficiently dispersed and well coupled to the epoxy matrix [4-6,15,17,21]. The very low tensile CV of F6 further suggests that, under the present preparation route, the selected MWCNT loading provided a strong and repeatable tensile-load response.

The GNP/epoxy system ranked second in peak tensile load and tied with MWCNT/epoxy in mean flexural strength. This agrees with recent graphene/GNP literature showing that platelet fillers can modify stress redistribution, crack paths and elastoplastic behaviour in epoxy and bonded-joint systems [9,22-24]. The larger tensile scatter of F7 compared with F6 may reflect sensitivity to platelet orientation, local agglomeration, incomplete wetting or spatial non-uniformity within the overlap. Thus, the result does not weaken the relevance of GNP; instead, it indicates that GNP is a promising single-filler modifier whose effectiveness may depend more strongly on processing uniformity.

Silica/epoxy and clay/epoxy produced moderate but meaningful changes. The stronger relative improvement in bending than in peak tensile load for silica is consistent with studies reporting that rigid silica particles can affect local stiffness, crack pinning and damage resistance, while their joint-level benefit depends on particle distribution, adhesive thickness and interfacial quality [7,13,14]. The clay result is also consistent with the literature showing that layered silicates may modify adhesion and strength but are sensitive to content, exfoliation/intercalation state and joint configuration [16,17]. In the present system, neither silica nor clay reached the balanced performance of the carbon fillers, but both contributed measurable bending improvement.

The BN/epoxy result should be interpreted within the selected loading and test configuration. At 0.3 wt.% BN, the formulation showed the weakest balanced response and a lower peak tensile load than neat epoxy. This does not imply that BN is generally unsuitable as an epoxy filler, because BN may provide stiffness, barrier, thermal or multifunctional advantages in other polymer systems. It indicates only that the present BN content, mixing route and epoxy-bonded GFRP geometry did not produce an effective static mechanical improvement in this screening study.

Comparison with representative literature (Table **6**) clarifies the similarities and differences. The carbon-filler advantage agrees with previous MWCNT/GNP

Table 6: Comparison between the Present Results and Representative Literature

Reference	Focus	Relevant finding	Relation to the present results
Zhou *et al*. [13]	Nano-silica/epoxy SLJs	Silica can improve adhesive response but depends on adhesive thickness and interfacial quality.	F9 improved bending more strongly than peak tensile load, consistent with filler effects being loading-mode dependent.
Razavi *et al*. [14]	Silica and MWCNT-reinforced structural adhesives	Combined particle/tube systems can alter shear strength and elongation in SLJs.	The present Q4 paper isolates the single-filler baselines before hybrid interpretation.
Cakir and Kinay [17]	MWCNT, silica and nanoclay in dissimilar bonded joints	Multiple nanofiller families were compared under one experimental framework.	The present study extends that logic to epoxy-bonded GFRP specimens with both tensile and bending indicators.
Özbek and Çakır [19]	MWCNT/nano-silica hybrids in GFRP plates	Mechanical and fracture behaviour can depend on filler family and loading mode.	The current single-filler screening explains why carbon fillers were retained as stronger baselines.
Venugopal and Sudhagar [22]	GNP-reinforced GFRP composite joints	GNP addition can influence both shear and flexural response in composite joints.	F7 confirmed a strong flexural response, tying with F6 in mean Rbb.
Abdalla *et al*. [24]	GNP effects on SLJ elastoplastic behaviour	Recent work supports the relevance of graphene reinforcement in SLJ behaviour.	The present results provide an experimental GNP baseline under a different epoxy/GFRP dataset.

Table 7: Normalized Screening Interpretation Combining Performance and Repeatability

Code	Formulation	Fm norm	Rbb norm	Balanced score	Mean CV (%)	Rank	Interpretive note
F14	Neat epoxy	0.448	0.233	0.341	10.79	5	Baseline neat-epoxy control used for percentage-change calculations.
F6	0.3 wt.% MWCNT	1.000	1.000	1.000	37.48	1	Best balanced single-filler system; highest tensile load and joint-best flexural strength, but bending variability requires process control.
F7	1 wt.% GNP	0.909	1.000	0.954	27.17	2	Strong carbon platelet system; tied for flexural strength and ranked second in tensile load.
F9	0.5 wt.% SiO_2	0.511	0.556	0.533	18.24	3	Moderate inorganic-particle modifier; improved bending more than tensile load.
F11	0.5 wt.% Clay	0.487	0.411	0.449	12.48	4	Moderate layered-silicate modifier; improved bending and tensile load, but less than carbon fillers.
F13	0.3 wt.% BN	0.290	0.274	0.282	7.10	6	Limited benefit at the selected loading; reduced tensile load relative to neat epoxy.

adhesive-joint studies reporting improved joint capacity when filler dispersion and load-transfer conditions are favourable [15,21-24]. The silica and clay results are consistent with studies showing that inorganic particle or layered-silicate additions can be beneficial but are strongly dependent on concentration, adhesive thickness, joint configuration and processing route [13,16,17]. The present study differs from many earlier reports by using the same epoxy/GFRP system, the same preparation route and both tensile and bending indicators for five single-filler families. This is why F6 and F7 were identified as the strongest single-filler baselines, while F9, F11 and F13 were interpreted as moderate or limited candidates rather than universally beneficial modifiers.

The results also demonstrate the importance of taking agglomeration and processability into account when choosing practical formulations. Nanofiller enhancement of the joint response is only meaningful when the reinforcement effect is larger than the increase in viscosity, clustering of the particles, local stress concentration and disruption of wetting. Formulation scatter can thus be as significant as formulation mean strength. The normalized screening interpretation in Table **7**, therefore, uses the tensile capacity, flexural capacity and mean CV together, instead of using a greatest value.

6. LIMITATIONS AND PRACTICAL IMPLICATIONS

This manuscript applies to a subset of single fillers under static single lap tensile loading and static three-point bending. This study did not include fatigue, environmental ageing, moisture exposure, temperature effects, impact loading or microscopic fracture-surface characterization. The discussion of crack bridging, crack deflection, load transfer and agglomeration is not microstructural evidence, but is a mechanical interpretation that is consistent with the evidence, supported by literature, and based on observations from macroscopic failure. Micro-dispersion assessment, characterization of fracture surfaces and testing on durability would be necessary for future structural qualification.

Based on the results, it is concluded that MWCNT and GNP are the most promising single filler modifiers for further development in this epoxy/GFRP bonding system for structural adhesive applications. But it is important that the selection of the formulation is not determined only by the maximum mean. The performance-repeatability map suggests that scatter, failure morphology and processing control should be taken into account when considering the need for high static capacity. In practical terms, the potential applications of carbon modified epoxy adhesives could be for increasing the static load capacity, but the qualification would require controlled mixing and dispersion, consistent bond line and durability evidence before service use.

7. CONCLUSIONS

The static response of epoxy-bonded GFRP composite joints was modified with single-nanofiller, but the amount and reliability of the modification was highly influenced by the filler family and loading mode. Among the selected formulation subset, the formulation of 0.3 wt.% MWCNT/epoxy (F6) recorded the highest mean peak tensile load of 4.1345 kN which is 123.1% higher than that of neat epoxy.

The GNP/epoxy formulation (F7) had second highest peak tensile load and equal highest mean flexural strength with MWCNT/epoxy. The mean flexural strength of both F6 and F7 were 67.50 MPa, which was an improvement of 328.6% compared to the neat epoxy control.

The silica/epoxy and clay/epoxy improved moderately, especially in bending, but neither of them showed satisfactory performance in terms of balance between peak tensile-load capacity and flexural performance. The mean peak tensile load compared to neat epoxy decreased while flexural properties improved slightly with BN/epoxy at 0.3 wt.%.

The screening results, both statistical and normalized, revealed MWCNT and GNP as the major single-filler candidates, and the coefficient of variation and results from macroscopic failure indicated that repeatability and control of the process are needed for the ranking of the formulation. Because of the lack of SEM or microscopic fracture analysis data, general statements about the strengthening mechanisms suggested in this paper must be regarded as evidence consistent conclusions rather than as microstructural conclusions.

In general, all the findings indicate that single-nanofiller screening is useful for the development of structural adhesives as it can differentiate between nanofillers that are high and moderate or even limited in performance when applied to the same epoxy system, GFRP adherend, preparation route and static testing conditions.

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CONFLICT OF INTEREST

The authors have no competing interests that would bias the results or interpretation of the data reported in this paper.

DATA AVAILABILITY

The selected raw data, descriptive statistics, Welch ANOVA results, Games-Howell comparisons, normalized screening metrics and high-resolution figure files are provided in the accompanying statistical workbook, CSV files and figure package prepared for journal submission.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work, the authors used ChatGPT by OpenAI to improve language clarity, manuscript organization and formatting. After using this tool, the authors reviewed and edited the content as necessary and take full responsibility for the content of the publication.

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